

RETROFITTING MASONRY INFILL WALLS WITH TEXTILE REINFORCED MORTAR

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SUMMARY:

The vulnerability of unreinforced masonry walls (URM) under seismic events, causing huge loss of money and human lives, has revealed the enormous need for an efficient strengthening material. In this context, the present paper reports the development of a new reinforcing material for masonry walls based on braided fibrous structures. These fibrous materials were developed through braiding of polyester yarns around a core made of either glass or carbon fiber (core reinforced braid) or without any core (simple braid). Masonry walls were fabricated by placing these braided materials on the surface of clay brick walls in a mesh like configuration and covering with a mortar layer. The flexural behavior of developed masonry walls was compared with URM and walls reinforced with more commonly used glass fiber laminates using the same configuration and process.

Keywords: half-timbered, cyclic tests, seismic behaviour, traditional connections

1 INTRODUCTION

The quality of the built heritage play a central role on the quality of daily human lives as they interact continuously with the built spaces, either in the work, social events and at home. In particular, the safety of the built spaces is indeed a demand of modern societies and remains a huge concern in prone seismic regions. It is known that seismic vulnerability is not exclusive of ancient masonry structures but affects also the built heritage from XX century, composed in a majority of reinforced concrete (RC) buildings, both in structural and non-structural elements. In this constructive typology, brick masonry walls represent the most traditional enclosure system and have demonstrated reasonable performance with respect to healthy indoor environment, temperature, noise, moisture, fire and durability, even if there has been some trend for improvement serviceability by purposing newly solutions (Lourenço et al. 2010). Masonry infills represent approximately 15% of the total construction volume.

Despite masonry infill walls have been considered for long time as non-structural elements, they can play a positive role in the seismic behavior of RC buildings, if their influence in the building response is correctly taken into account (Chiou et al. 1999, Al-Chaar et al. 2002). Conversely, they need to be checked against in-plane severe damage and possible out-of-plane collapse. Indeed, as demonstrated by recent earthquakes in Turkey (Kocaeli 1999, Duzce 1999, Bingol 2003), Italy (L'Aquila, 2009) and Spain (Lorca, 2011) demonstrated the vulnerability of non-loadbearing unreinforced masonry walls acting as infill of reinforced concrete frames, the inefficient behavior of masonry infills can result in extensive economic losses, resulting in low levels of reparability, and in the loss of human lives. This situation raises the need of improvement of the construction technology and design of non-structural elements for new buildings and of retrofitting in case of existing buildings. The latter aspect is the focus of this paper. Indeed, it is of paramount importance to act promptly in the retrofitting of masonry infill walls, taken into account that great part of RC buildings was designed before the advent of seismic regulations. With this respect, some guidelines are provided in some international codes but in a majority of countries there are no standardized guidelines for the retrofitting of masonry infills.

This paper intends to provide: (1) information on the seismic behavior of masonry infill walls under seismic action, by focusing on post mortem survey in recent earthquakes; (2) a brief overview of the retrofitting techniques of masonry infill walls and description of the proposed technique based on textile reinforced mortar; (3) experimental results of flexural tests on typical masonry infills used in reinforced concrete framed structures reinforced with textile reinforced mortar; (4) assessment of the performance of the presented retrofitting technique for the enhancement of the masonry infill walls.

2 TIPOLOGY OF MASONRY INFILL WALLS

The brick masonry walls as non-loadbearing elements have been used since the generalized adoption of the reinforced concrete as a main structural system in Portugal, which dates back to 1960. In Figure 1 one can see the evolution of masonry walls in Portugal during the xx century:

- a) decade of 40: single leaf walls in stone masonry;
- b) decade of 50: stone masonry walls with a internal leaf in brick masonry;
- c) decade of 60: Cavity Wall with brick masonry with thick external leaf;
- d) decade of 70: Cavity Wall with brick masonry with médium thickness;
- e) decade of 80: Cavity Wall with brick masonry with médium thickness with termal insolation in between the leaves;
- f) decade of 90: Single leaf walls with external termal insulation

The single walls become to be used again with the solution of vertically perforated brick masonry units, being associated to innovative solution of external thermal insulations solution (Pereira 2010).

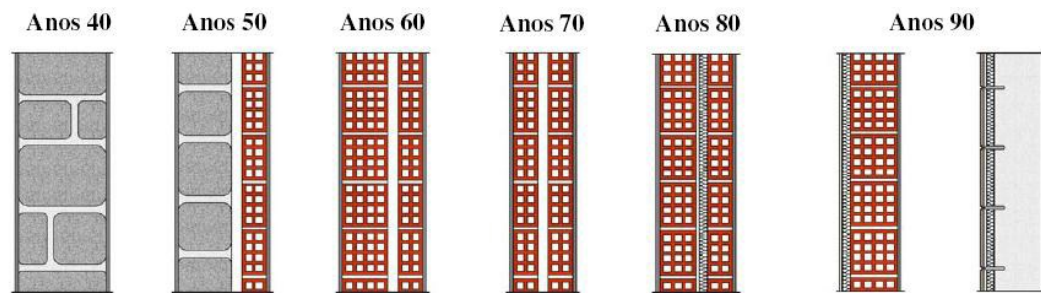


Figure 1. Evolution of non-loadbearing brick masonry walls in Portugal (Pereira 2010)

3 BEHAVIOR OF MASONRY INFILL WALLS UNDER SEISMIC LOADING - A BRIEF REVIEW

Masonry infills are not considered as structural elements, as they do not have to bear vertical loads, and, thus, no specific design guidelines are provided in design codes, including Eurocode 8 (2004). However, in case of occurrence of earthquakes they can have an active role on the global resisting mechanism of the RC masonry infilled frames. The problem of the interaction between infill and RC frames, on how the infills influence the structural response, has been object of many experimental and numerical research (Calvi and Bolognini 2001, Dolsek and Fajfar, D'Áyala 2008). According to past research (D'Áyala 2008, Pujol and Fick 2010; El-Dakhakhni et al. 2006, Fardis 2006) it is known that masonry infills can have a beneficial effect under controlled damage, when it develops before the maximum shear forces occur, being able to dissipate energy and control inter-storey lateral drifts of RC frames. However, it very often happens that damage and collapse of RC buildings is due to improper consideration of, or neglecting, the infill walls influence on the surrounding RC elements. Indeed, the negative effect of the masonry infills is related to the soft storey and torsional effects, due to irregular distribution of masonry walls in height and in plan respectively. Masonry infills can be unfavourable when leave a short portion of the column clear, leading to the shear collapse of the columns (Chiou et al. 1999). It should stressed that the unfavourable effect of infills can also result from its own inefficiency in developing in-plane resisting mechanisms under large deformations imposed by enclosing frames leading to its severe damage (El-Dakhakhni et al. 2006).

The inadequate in-plane behavior of infills can also prevent the developing of out-of-plane resisting mechanism by arching effect (Fardis 2006). In addition, the detachment from the surrounding frame elements at early stages of the seismic event and the absence of efficient connections to RC frames results in their out-of-plane collapse. This type of deficiency has been shown to be worrying from the last recent earthquakes.

3.1 The example of recent earthquakes

According to (Karakostas et al. 2005), after the Lefkada earthquake in Greece in 2003, it was seen that the major damage was concentrated at the non-structural elements, particularly in clay masonry infills, including out-of-plane collapses, shear cracking and detachment of the walls from enclosing frames. From the recent earthquake of L'Áquila in 2009, in Italy, and apart from the collapse of rural masonry residential buildings, it was observed that widespread extensive damage in masonry infill walls and internal partition walls developed, being responsible for the highest losses in RC buildings. This type of non-structural damage requires in general high investment as it requires extensive repair, or in case of low reparability, results in the demolition and reconstruction, resulting in a major waste of time and money. The major concern about the out-of-plane vulnerability of masonry infills is the lack of detailing at the level of materials, connections to the surrounding RC frames and absence of fastener elements in case of cavity walls, resulting often in the complete and independent collapse of the leaves, see Figure 2.



Figure 2. Failure patterns of masonry infill walls found in the recent earthquake of L'Áquila

4 USE OF REINFORCED TEXTILE MORTAR AS A RETROFITTING TECHNIQUE

The development of textile materials starts with the development of high-performance fibres such as fiberglass (in the 30s) and carbon fibres (early 60s), developed for high technology industry such as the aeronautics. Its application in the building industry as part of reinforcement of cement-based materials starts in the beginning of the 80s, and they were through a slow process of investigation until the late 90s (Triantafillou and Papanicolaou 2006). Textile reinforcing materials, viewed as a material highly resistant to tensile stresses, can be embedded in a mortar matrix that acts as the bonding agent with the main structure to be reinforced. These materials consist on long woven, knitted or even unwoven fiber rovings in at least two directions. The first investigated solutions were related to its tensile properties and its application to reinforcement of reinforced concrete structures, which made it suitable for the reinforcement of beams (both for bending and shear) or the jacketing and confining concrete columns. The application as a method of jacketing for retrofitting masonry walls is a relatively new concept still under investigation. Nonetheless, it is already one of the recommended reparation techniques in some guidelines. Among the parameters that affect the performance of the textile mortar reinforcement, there are some remarkable ones: (1) density of the mesh, depending on quantity of fibres in each thread (defined by mass) and the separation among them; (2) properties of the mortar, affecting the bond between the element and the reinforcement; (3) properties of both mortar and textile surfaces, affecting the bond among them to make the composite adequately.

Textile reinforced mortar (TRM) is being developed mainly as an alternative retrofitting technique to glass or carbon fiber reinforced polymers (GFRP, CFRP), that have been a great development and widespread use in the field of structural strengthening. Nevertheless, some disadvantages, mainly linked to the use of resins as bonding agents, are leading to the investigation of other materials of similar behavior. Some of the most important disadvantages are: (1) high costs due to both the materials and the requirement of highly skilled workmanship; (2) need of good protection against fire action, given its very low performance in this situations; (3) impermeability both to water and to vapour, that can lead to bond problems; (4) hazards of using resins: dissolvent, toxic vapours, etc.; (5) difficult reversibility of the strengthening, which is specially problematic for historical structures or in cases where problems such as cracking must be checked afterwards.

The use of an inorganic matrix would solve most of these problems, given that the properties of cementitious binders are more alike to the properties of concrete, and also masonry. Nonetheless, its behavior is not still fully investigated and there are many parameters that must be studied to get to a better understanding of the behavior of this material, as well as its advantages when compared to other reinforcement techniques. Studies by Papanicolau and Triantafillou have compared the performance of FRP and TRM for many applications, namely for strengthening masonry for both in-plane and out-of-plane actions (Triantafillou and Papanicolaou 2006; Papanicolaou et al. 2007). For in-plane loading, they found that, compared with a FRP reinforcement of the same fibre density, TRM had an effectiveness of 60-70%. In general, but specially for out-of plane actions (which are usually the ones to cause major damage and potential victims during earthquakes), TRM is a very promising technique, thanks to its capacity of rising highly deformability of the infill walls before the collapse, as well as its strength.

5 TEXTILE BRAIDED REINFORCEMENTS

In this work, textile reinforced mortar (TRM) retrofitting technique is analysed in case of brick masonry, characteristic of typical masonry infill walls. The proposal is to use TRM for enhancing the out-of-plane behavior of brick masonry. The reinforcement material are composed of textile braided wires, in which glass or carbon fibers should be introduced to form the final reinforcing bars, see **Figure 3a**.

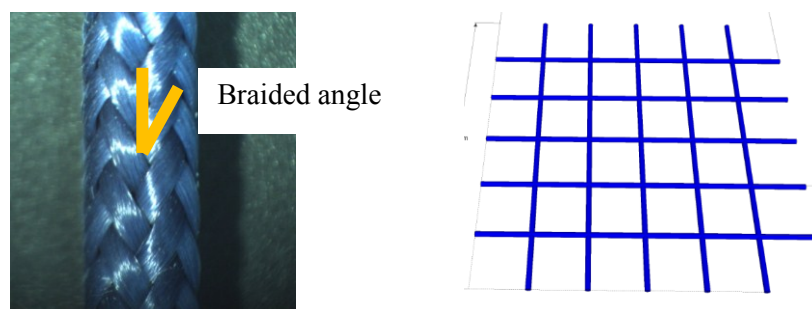


Figure 3. Examples of the polyester braided yarns; (a) example of polyester braided yarn; (b) textile braided mesh

The manufacture technique for braided yarns was used for the first time two hundred years ago (Cagri Ayranci 2007) and is increasingly used for the production of technical textile materials. This technique consists of braiding of wires in the longitudinal and transversal directions, forming a tubular structure. This technique has been also used in the production of reinforced concrete (Pereira et al. 2007). The wires find in two groups of wires which circulate in opposite orientations. The braided yarns were manufactured in a coil-winder at a rate of 10m/min, see **Figure 4**. The material used for the wires used in the structures was the polyester of high tenacity.

It is foreseen that the braided technique production for the braided composite materials can be used with advantages in the strengthening of masonry walls due to its simplicity and ability to dispose

axially the fibers. Besides, the braided composite yarns have the advantage of protecting the axial reinforcements enabling that the material does not suffer physical alterations during the application process in masonry walls. Additionally, it is foreseen that better bond properties can be found between mortar and the reinforcing materials.

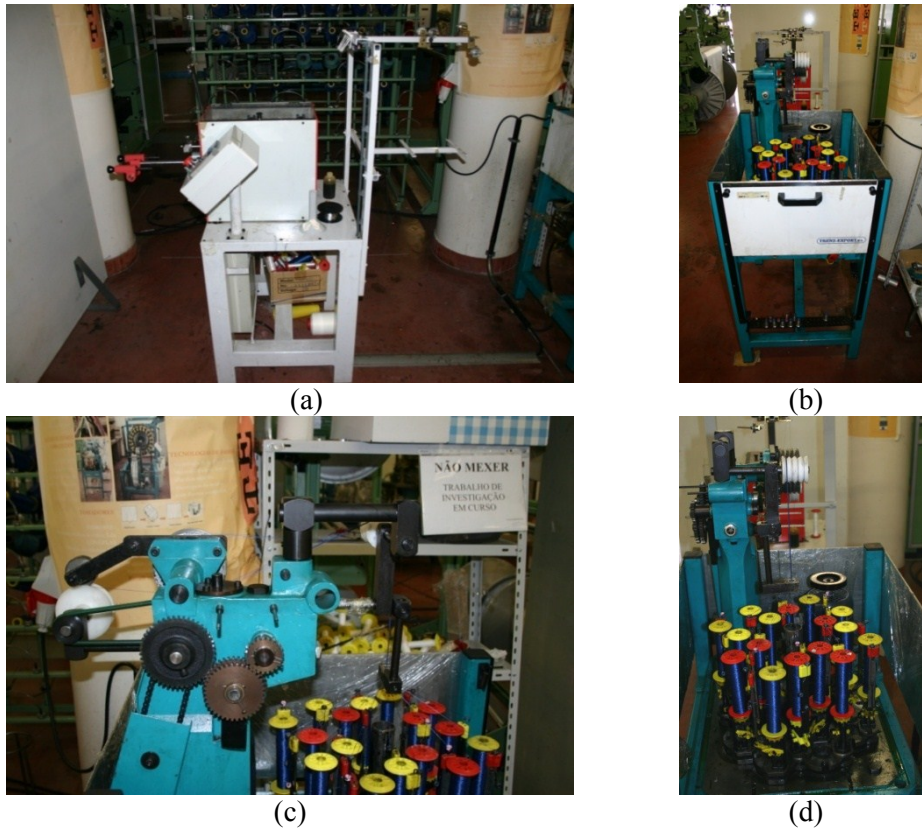


Figure 4. Equipment for manufacture the textile braided yarns; (a) coil-winder; (b) vertical braiding; (c) pulling system; (d) spindle group

In this work two types of braided composite yarns were considered for the retrofitting of masonry walls, namely, polyester braided yarns filled with glass and carbon fibers aiming at improving the mechanical properties, namely the tensile strength. The idea is also to introduce natural fibers, like flax, sisal or even basalt but this is in development as the workability of the natural fibers is reduced. Given that the linear mass of the carbon fibers is the double (1200g/km) of the linear mass of the glass (600g/km), it was decided to introduce in each polyester braided yarn two wires of carbon and four wires of glass. The idea is then to combine the braided yarns in perpendicular directions and that be embedded in the rendering mortar of the masonry walls.

The simple polyester braided yarns and the composite braided yarns (filled with glass and carbon fibers) were tested to uniaxial tensile loading in order to have an idea about its tensile behavior. The tensile behavior of one braided yarn (simple or filled with carbon or glass fibers) is shown in stress-deformation diagrams presented in **Figure 5**. It is seen that simple braided yarn presents clear distinct behavior from the braided composite structure. The simple polyester yarn is considerable deformable and presents lower tensile strength (average of 244MPa). The deformability of the simple braided structure is associated to the possibility of variation of the braided angle during the loading procedure, which is decreasing as the tensile loading increase. The pre-peak regime of the composite structures is characterized by a clear higher stiffness. Notice that in case of composite yarns, the braided structure is previously strained, which eliminate the possibility of changing the structure during the tensile test. This led to initial higher elastic modulus, which changed from 2.0GPa (simple structure) to 16.8GPa (glass braided yarn) and 28.3GPa (carbon braided yarn). The average tensile strength found for the carbon and glass braided structures is of 618MPa (coefficient of variation of 12.9%) and 615MPa (coefficient of variation of 9.9%) respectively.

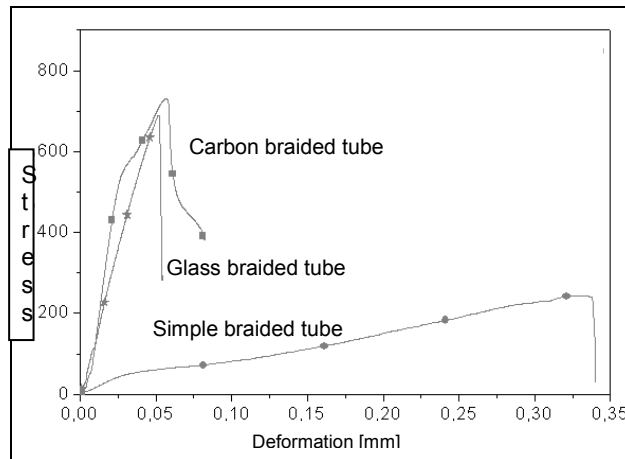


Figure 5. Stress-deformation diagram for the braided structures under tensile loading

With respect to post-peak behavior, it is observed that the glass braided yarn present a very fragile behavior as there is no possibility to record any deformation after the peak tensile strength is reached. The carbon braided structures presents a more ductile behavior when compared to the glass structures, even if it cannot be considered properly as a ductile material. This behavior is directly associated to the failure mode of the composite braided structures. In effect, the failure of the glass braided yarns is sudden, whereas the failure of carbon braided yarns occurs after the total rupture of the wires, which does not happen at the same time.

6 ANALYSIS OF THE EFFECTIVENESS OF THE BRAIDED STRUCTURES AS RETROFITTING MATERIALS

Aiming at evaluating the performance of the textile braided materials as retrofitting technique to improve the out-of-plane behavior of masonry walls, it was decided to carry out a set of bending tests on unreinforced and reinforced masonry specimens representative of typical masonry infill walls. The brick masonry units have horizontal perforation and a thickness of 150mm. At this first phase, for the bending tests only the direction perpendicular to the bed joints was considered. The dimensions adopted for the specimens ($0.65 \times 0.65 \text{ m}^2$) were defined according to European standard EN 1052-2 (1999), see Figure 6a. The textile braided yarns were combined in the two directions having a spacing of 100mm in each direction, see Figure 6a. The total mass of the textile braided yarns was the same when carbon and glass fibers are used, being approximately 101 g/m^2 . In order to simplify the work, it was decided to apply the reinforced mortar only at one face of the masonry specimens. Besides the specimens reinforced with textile braided mesh, namely three specimens with carbon braided mesh (AEC), glass braided mesh (AEV) and simple braided mesh (AES), three unreinforced specimens (AS) were also considered so that the performance of the retrofitting technique could be evaluated. Additionally, three specimens with truss type bed joint reinforcement (AJA), corresponding to reinforcement ratio of approximately 0.05%, and three specimens reinforced with glued glass fibers to the rendering mortar were also adopted. The glass wraps have 10mm width and 1mm thickness and 200mm spacing so that the same mass of reinforcement is used when compared to textile braided meshes. The masonry specimens were built by an experienced mason with a general proposed pre-mixed mortar M10. The rendering of the specimens was made seven days later with a pre-mixed mortar specially used for rendering. The truss type reinforcement was applied during the construction of the masonry specimens, whereas as the application of the textile braided meshes were applied during the rendering procedure. Given the flexibility of the textile braided materials, the meshes were previously positioned, fixed and pre-stressed with a system composed of steel bars and stressing devices fixed in the opposite side of the specimen to which the reinforcing meshes were positioned (Abreu 2011). After the positioning and tensioning, the rendering was applied by the same experienced mason. A rendering thickness of approximately 20mm was considered.

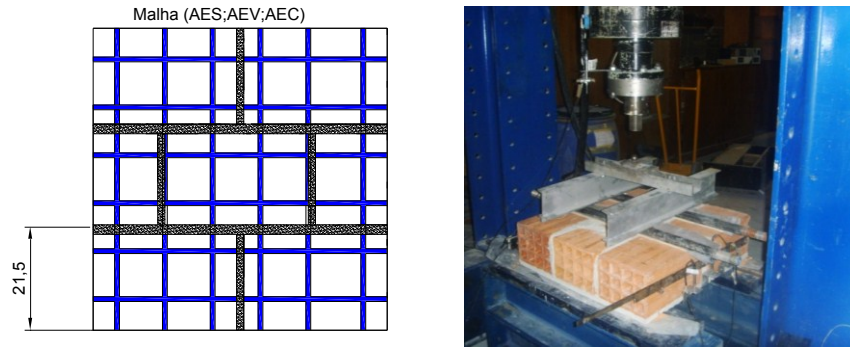


Figure 6. Details of experimental campaign on four point bending tests; (a) masonry specimens and configuration of the textile braided mesh; (2) test setup

The glass wrap were glued to the rendering 21 days after the rendering and 7 days before the bending test, so that the glue is able to dry. The bending tests were carried out according to the European standard EN 1052-2 (1999). The vertical load was applied by means of an actuator with a capacity of 200kN, connected to a steel frame which instead is connected to a reaction slab, taking into account the loading configuration suggested in EN 1052-2 (1999) (four point bending configuration), see Figure 6b. The distance between the loading points was 200mm. The minimization of friction in the supports was taken into account. The bending tests were carried out under displacement control through a LVDT (linear voltage displacement transducer) connected to the vertical actuator. The deformation of the masonry specimens was recorded by three LVDTs measuring the vertical displacement at the mid span and the displacement between the mid span and the supports. The bending tests were carried out 28 days after the rendering and the application of the reinforcement.

The stress-displacement diagrams found for each masonry specimen typology are shown in **Figure 7**. The unreinforced masonry (**Figure 7a**) is characterized by a very brittle behavior, which is associated to the localized central crack involving the failure of the unit-mortar interface and the units, see **Figure 8a**. This is the typical failure mode already pointed out by Pereira (2010). The flexural behavior of the masonry specimens strengthened with simple braided mesh is similar to the unreinforced masonry but presents a slight increase on the flexural strength of 8.7% calculated based on the average values. However, the brittle behavior is not avoided, even if the maximum vertical displacement is increased, which is associated to the concavity shown at the beginning of the test. In case of masonry reinforced with glass braided composite materials, it is seen that the specimens behaves in a similar way in the pre-peak regime with no changes on the flexural stiffness. The great difference is in relation to the post-peak behavior. Firstly, there is an important variability of the maximum flexural strength, being of 0.34MPa for specimen AEV1 and of 0.49MPa in specimen AEV2. It appears that both specimens present a similar behavior until the value of strength of 0.34MPa. After this value, the specimen AEV1 exhibit a reduction on the strength and a progressive recover for increasing deformation. Specimen AEV2 presents a clear change on the stiffness for a stress of about 0.32MPa, after which the resistance continues to increase up to a value of 0.49MPa. The use of glass braided meshes results in the improvement if the flexural strength of about 9.8% and an increase on the deformation of about 450%. The maximum resistance is mobilized for a considerable deformation. It should be stressed that additional tests have to be done in order to clarify in a better way the performance of the glass braided meshes, but it is possible in any case to conclude about the trend for the increase on the flexural strength and particularly to the increase on the deformability. The behavior of the three specimens with carbon braided mesh (AEC) is quite similar to the behavior of specimen AEV2. The stress increase up to a level after which there is a decrease on the resistance and subsequent recover and even an increase on the flexural strength is recorded after the first peak. The flexural stiffness is higher than the stiffness of specimens reinforced with glass braided meshes. The reduction of the resistance occurs approximately for a displacement close to the deformation corresponding to maximum load of unreinforced masonry specimens.

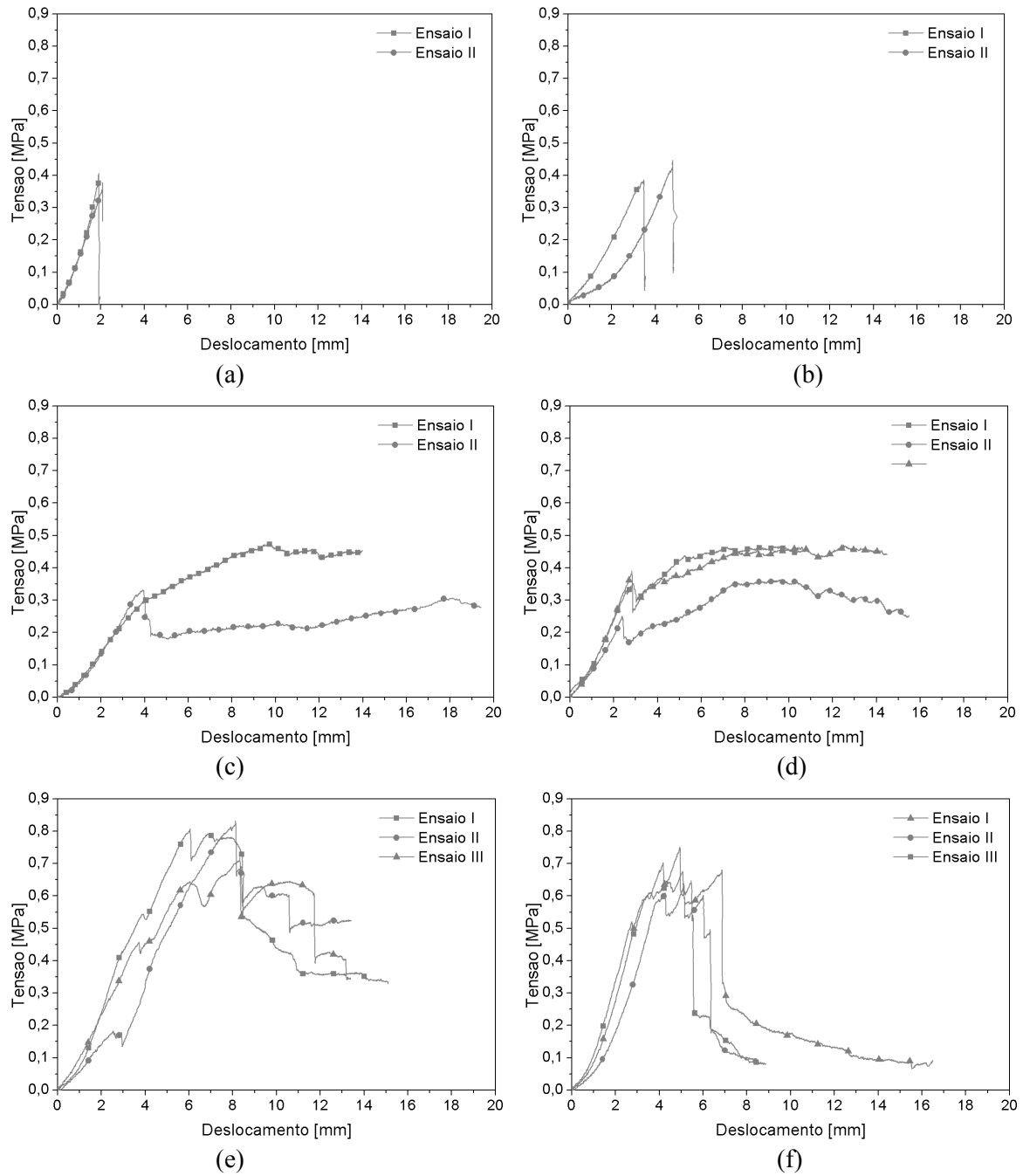


Figure 7. Stress-displacement diagrams found for the specimen typology; (a) unreinforced masonry specimens; (b) simple polyester braided mesh; (c) glass braided mesh (d) carbon braided mesh; (e) truss type reinforcement; (f) warp glass mesh

The flexural stiffness is higher than the stiffness of specimens reinforced with glass braided meshes. The reduction of the resistance occurs approximately for a displacement close to the deformation corresponding to maximum load of unreinforced masonry specimens. This appears to indicate that the first peak corresponds to the opening and localization of the crack, being accompanied by a reduction on the resistance of approximately 20%. After this, there is a stress transfer between the masonry to the reinforcing mesh. The flexural resistance increases up to a level higher than the first peak, which can be associated to the contribution of the reinforcing materials. In fact, in terms of resistance, the composite braided meshes only contribute after the opening of the crack and this contribution is associated to the development of high deformations. In general, the increase on the ultimate deformation is about 322% and the increase on the resistance if of 17.5% in relation to the

unreinforced masonry specimens. The great advantage of the composite braided meshes is the prevention of brittle failure and the complete separation of the specimens in two parts, even if they cannot avoid the crack localization. The reinforcing materials are able to connect both lips of the crack of the specimens and the projection of materials, which represent a great advantage in relation to the unreinforced masonry in relation to the occurrence of seismic actions, see **Figure 8b,c**. It is believed that the mobilization of so great deformation is related to the debonding between the rendering mortar and the composite braided materials, see **Figure 8d**.

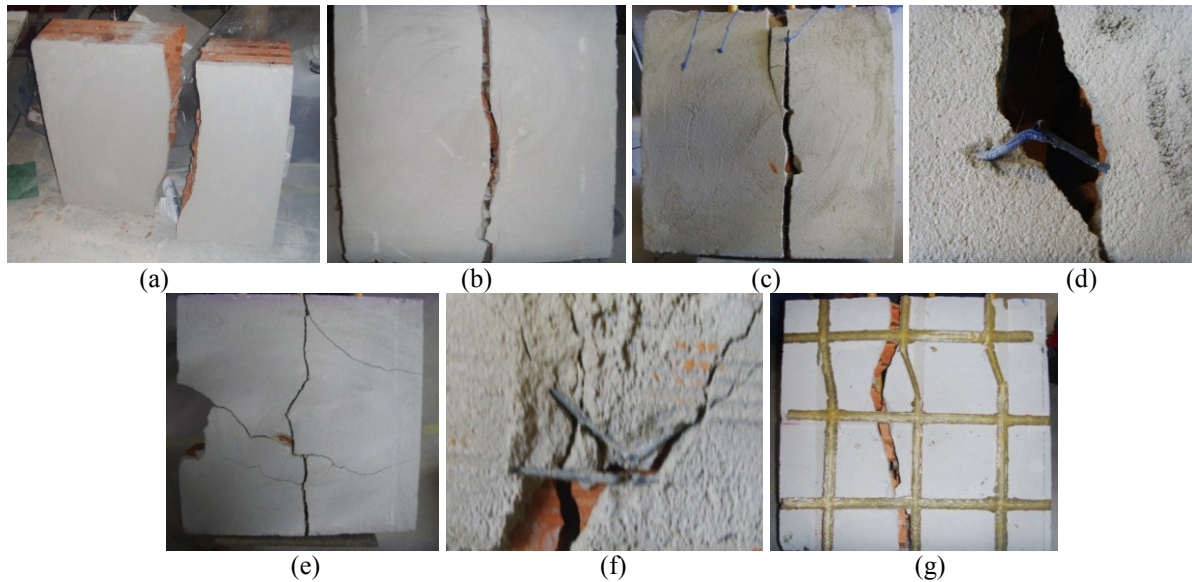


Figure 8. Failure modes of the masonry specimens; (a) unreinforced masonry specimens; (b); glass braided mesh strengthening (c) carbon braided mesh strengthening; (d) detail of the crack and carbon braided yarn; (e) masonry with truss type bed reinforcement; (f) detail of the failure of the weld of the reinforcement; (g) wrap glass reinforcement

In average, the flexural resistance of masonry specimens reinforced with truss bed joint reinforcement increase to the double, when compared to the unreinforced masonry specimens. The pre-peak behavior is characterized by the stress oscillation, which should be associated to the cracking of the bricks, see **Figure 7e**. It is seen that some irregularity characterized the zone of the peak stress, after which a descending branch develops with a reduction of the flexural strength. This behavior differs clearly from the specimens retrofitted with composite braided meshes. The crack pattern of these specimens is characterized by a major crack at the central zone of the specimens with some horizontal distributed crack, see **Figure 8e**. In some cases, some detachment of material occurs. The irregularity of the post-peak behavior can be in certain extent attributed to the breakage of the weld between the longitudinal and diagonal bars of the truss type reinforcement, see **Figure 8f**.

The behavior of retrofitted masonry specimens with glued glass wrap on the rendering is characterized by a linear pre-peak behavior and by a considerable oscillation of the peak stress, see **Figure 7f**. This can be explained by the continuous debonding between the glass wrap and the rendering. This means that the peak stress is in certain extent conditioned by the bond resistance of the composite material. The flexural resistance is in average 85% higher when compared to the unreinforced masonry specimens. The break of the bond the glass wrap also justifies the abrupt reduction of the flexural strength immediately after the peak stress, see **Figure 7f**. The abrupt stress reduction is followed by a more smooth stress reduction, which can be attributed to the remaining interlocking between both lips of the main crack, ensure by the reinforcement. Also in this typology, the central crack localization occurs and it clear that the increase on the crack opening is due to the deboning debonding of the glass wraps, see **Figure 8g**.

7 CONCLUSIONS

The behaviour of masonry infill walls under seismic action is often characterized by out-of-plane brittle failures, which results in high repair costs and feasibility of loss of human lives. This seismic vulnerability lead to the need of using retrofitting techniques, not only at the level of masonry walls but also at the level of the connections between masonry infill and enclosure structural elements. In this work the retrofit of masonry walls under lateral flexural loading is investigated taking into account a novel retrofitting material composed of textile composite braided meshes embedded in the rendering mortar. The meshes are composed of a polyester textile yarn in which carbon, glass or basalt fibers can be introduced.. The use of textile braided meshes with carbon or glass fibers embedded in the rendering mortar revealed to be a promising retrofitting technique as it leads to the increase on the flexural behaviour, even if it is not very significative, when compared to other solution retrofitting solution. However, the post-peak behaviour characterized by high deformation with almost no degradation of the flexural strength represents a major advantage over more classic retrofitting techniques. Additional studies on this retrofitting technique of masonry infill walls are being now made at university of Minho in the scope of a national research founded project.

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